Course discussion/Q&A

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Language Models

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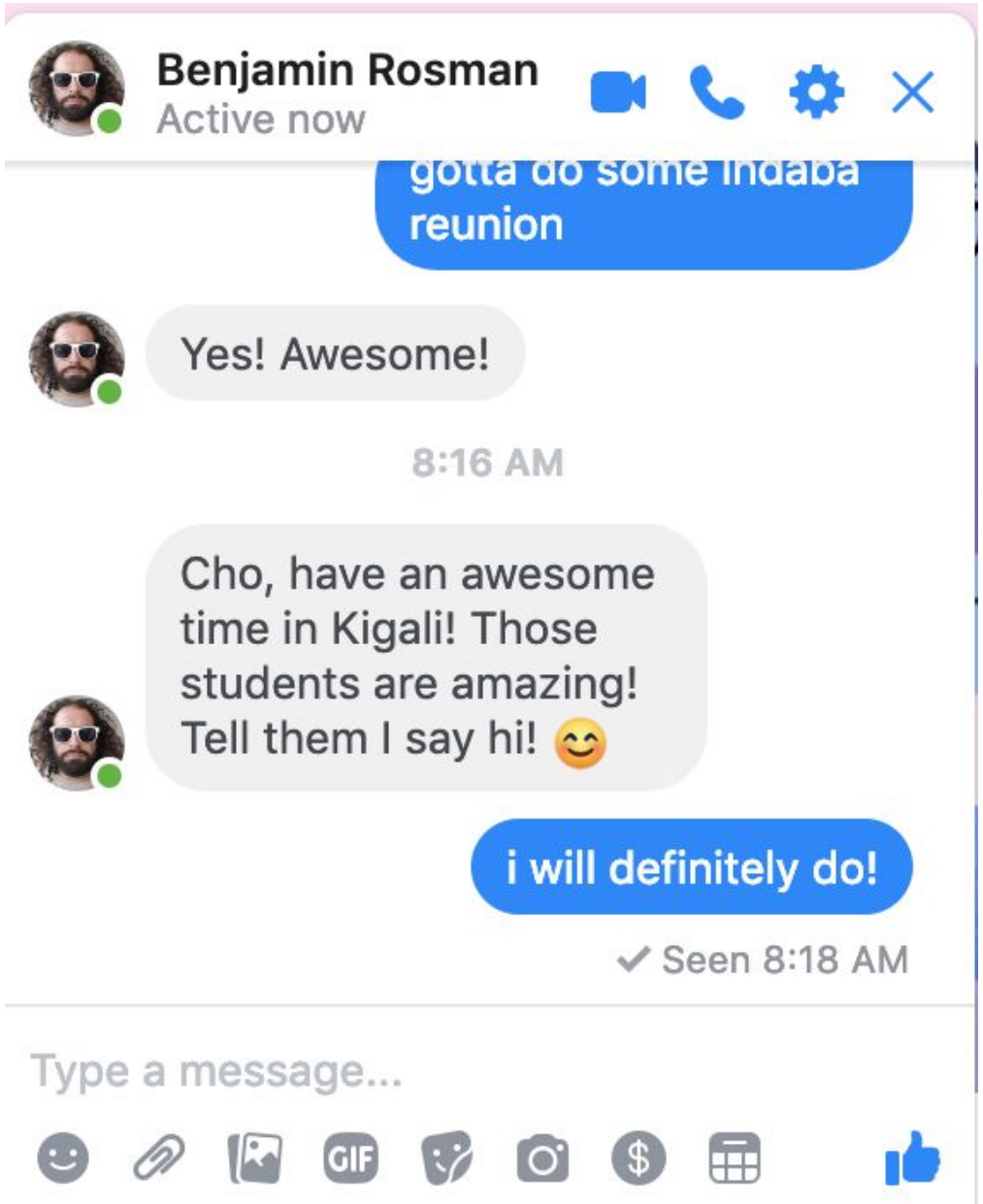
Before we start



Recap: Supervised Machine Learning

You all know already, but it's important enough to warrant repetition.

Supervised Learning – Overview

- Provided:
  1. a set of N input-output "training" examples
     $D = \{(x_1, y_1), \ldots, (x_N, y_N)\}$
  2. A per-example loss function⋆
     $l(M(x), y) \geq 0$
  3. Evaluation sets*: validation and test examples $D_{\text{val}}, D_{\text{test}}$
- What we must decide:
  1. Hypothesis sets $\mathcal{H}_1, \ldots, \mathcal{H}_M$
     - Each set consists of all compatible models
  2. Optimization algorithm

⋆ Often it is necessary to design a loss function.

* Often these sets are created by holding out subsets of training examples.

Supervised Learning – Overview

- Given:
  1. $D = \{(x_1, y_1), \ldots, (x_N, y_N)\}$ and $D_{\text{val}}, D_{\text{test}}$
  2. $l(M(x), y) \geq 0$
  3. $\mathcal{H}_1, \ldots, \mathcal{H}_M$
  4. Optimization algorithm
- Supervised learning finds an appropriate algorithm/model automatically
  1. For each hypothesis set $\mathcal{H}_m$, find the best model:*

$$\hat{M}_m = \arg \min_{M \in \mathcal{H}_m} \sum_{n=1}^{N} l(M(x_n), y_n)$$

using the optimization algorithm.

Supervised Learning – Overview

- Given:
  1. $D = \{(x_1, y_1), \ldots, (x_N, y_N)\}$ and $D_{\text{val}}, D_{\text{test}}$
  2. $l(M(x), y) \geq 0$
  3. $\mathcal{H}_1, \ldots, \mathcal{H}_M$
  4. Optimization algorithm
- Supervised learning finds an appropriate algorithm/model automatically
  1. [Training] For each hypothesis set $\mathcal{H}_m$, find the best model:*

$$\hat{M}_m = \arg \min_{M \in \mathcal{H}_m} \sum_{n=1}^{N} l(M(x_n), y_n)$$

using the optimization algorithm and the **training set**.

Supervised Learning – Overview

- Given:
  1. $D = \{(x_1, y_1), \ldots, (x_N, y_N)\}$ and $D_{\text{val}}, D_{\text{test}}$
  2. $l(M(x), y) \geq 0$
  3. $\mathcal{H}_1, \ldots, \mathcal{H}_M$
  4. Optimization algorithm
- Supervised learning finds an appropriate algorithm/model automatically
  1. [Model Selection]* Among the trained models, select the best one

$$\hat{M} = \arg\min_{M \in \{\mathcal{H}_1, \ldots, \mathcal{H}_M\}} \sum_{(x,y) \in D_{\text{val}}} l(M(x), y)$$

using the **validation set** loss.

* If you're familiar with deep learning, "hyperparameter optimization" may be a more familiar term for you.

Supervised Learning – Overview

- Given:
  1. $D = \{(x_1, y_1), \ldots, (x_N, y_N)\}$ and $D_{\text{val}}, D_{\text{test}}$
  2. $l(M(x), y) \geq 0$
  3. $\mathcal{H}_1, \ldots, \mathcal{H}_M$
  4. Optimization algorithm
- Supervised learning finds an appropriate algorithm/model automatically
  3. [Reporting] Report how well the best model *would* work

$$R(\hat{M}) \approx \frac{1}{|D_{\text{test}}|} \sum_{(x,y) \in D_{\text{test}}} l(\hat{M}(x), y)$$

using the **test set** loss.

* If you're familiar with deep learning, "hyperparameter optimization" may be a more familiar term for you.

Supervised Learning – Overview

- Given:
  1. $D = \{(x_1, y_1), \ldots, (x_N, y_N)\}$ and $D_{\text{val}}, D_{\text{test}}$
  2. $l(M(x), y) \geq 0$
  3. $\mathcal{H}_1, \ldots, \mathcal{H}_M$
  4. Optimization algorithm
- Supervised learning finds an appropriate algorithm/model automatically
- It results in an algorithm $\hat{M}$ with an expected performance of $R(\hat{M})$

Supervised Learning

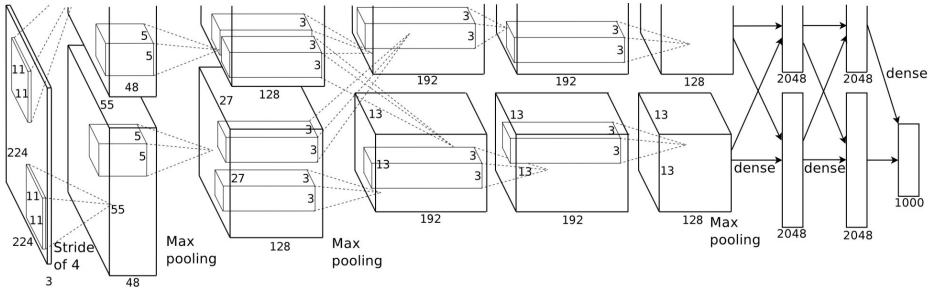
- Three points to consider both in research and in practice
  1. How do we decide/design a **hypothesis set**?
  2. How do we decide a **loss function**?
  3. How do we **optimize** the loss function?

Hypothesis set – Neural Networks

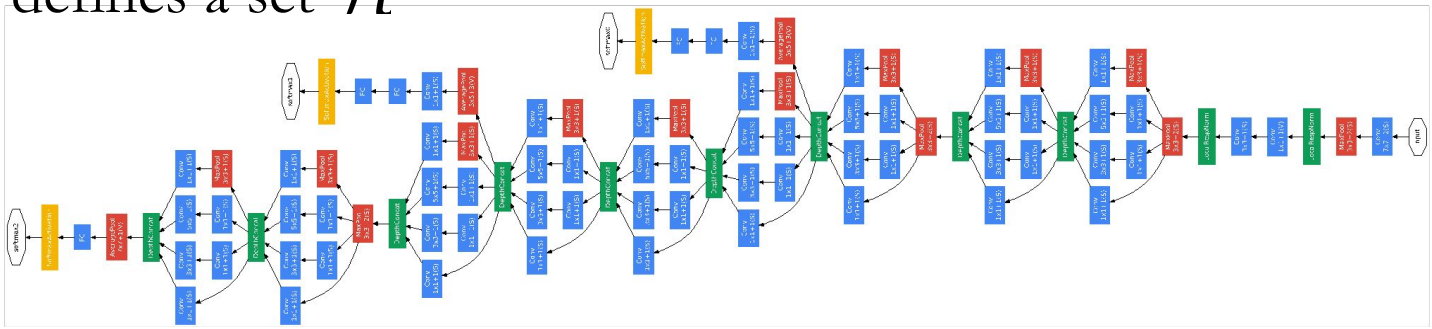
- What kind of machine learning approach will we consider?
  - Classification:
    - Support vector machines, Naïve Bayes classifier, logistic regression, …?
  - Regression:
    - Support vector regression, Linear regression, Gaussian process, …?
- How are the hyperparameters sets?
  - Support vector machines: regularization coefficient C
  - Gaussian process: kernel function $k(\cdot, \cdot)$

Hypothesis set – Neural Networks

- In the case of deep learning/artificial neural networks,
  1. The architecture of a network defines a set $\mathcal{H}$



vs.

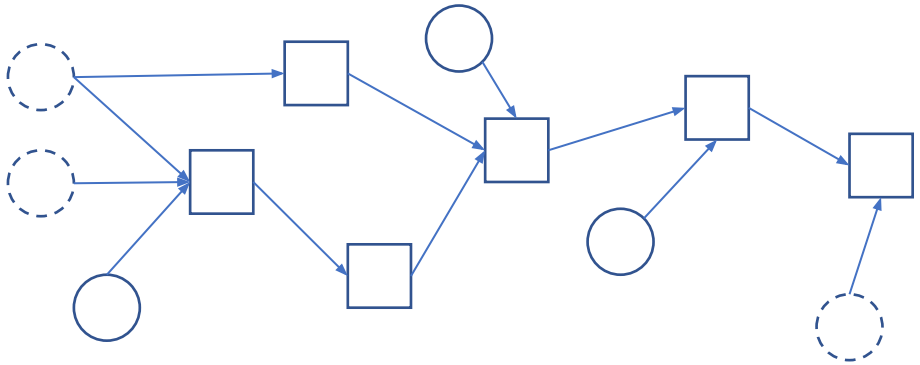


  2. Each model in the set $M \in \mathcal{H}$ is characterized by its parameters θ
     - Weights and bias vectors define one model in the hypothesis set.

- There are infinitely many models in a hypothesis set.
- We use optimization to find "a" good model from the hypothesis set.

Network Architectures

- What is a neural network? – An (arbitrary) directed acyclic graph (DAG)



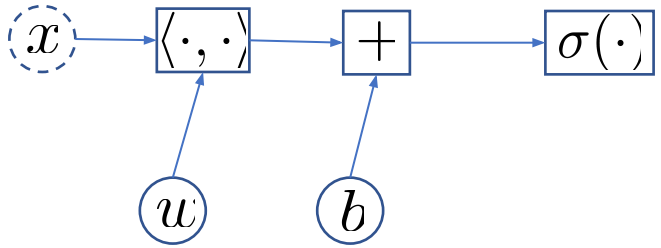
1. Solid Circles ○ : parameters (to be estimated or found)
2. Dashed Circles ◌ : vector inputs/outputs (given as a training example)
3. Squares □ : compute nodes (functions, often continuous/differentiable)

Network Architectures

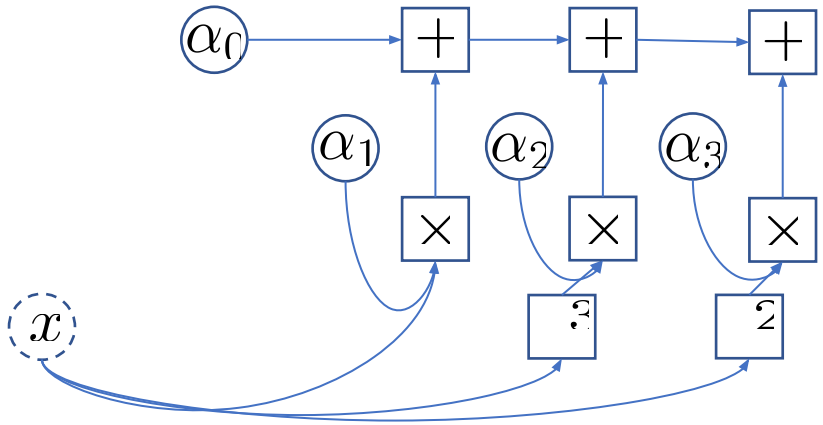
- What is a neural network? – An (arbitrary) directed acyclic graph (DAG)

1. Logistic regression

$$p_\theta(y=1|x) = \sigma(w^\top x + b) = \frac{1}{1+\exp(-w^\top x - b)}$$



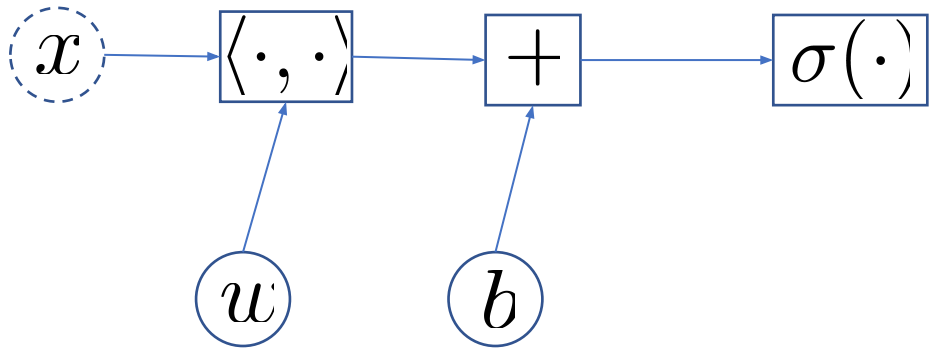
2. 3rd-order polynomial function $y = \alpha_0 + \alpha_1 x + \alpha_2 x^2 + \alpha_3 x^3$



Inference – Forward Computation

- What is a neural network? – An (arbitrary) directed acyclic graph (DAG)
- Forward computation: how you "use" a trained neural network.
  - Topological sweep (breadth-first)
  - Logistic regression

$$p_\theta(y = 1|x) = \sigma(w^\top x + b) = \frac{1}{1 + \exp(-w^\top x - b)}$$



DAG ↔ Hypothesis Set

- What is a neural network? – An (arbitrary) directed acyclic graph (DAG)
- Implication in practice
  - Naturally supports high-level abstraction
  - Object-oriented paradigm fits well.*
    - Base classes: variable (input/output) node, operation node
    - Define the internal various types of variables and operations by inheritance
  - Maximal code reusability
    - See the success of PyTorch, TensorFlow, DyNet, Theano, …
- You define a hypothesis set by designing a directed acyclic graph.
- The hypothesis space is then a set of all possible parameter settings.

* Functional programming as well

Supervised Learning

- Three points to consider both in research and in practice
  1. How do we decide/design a **hypothesis set**?
  2. How do we decide a **loss function**?
  3. How do we **optimize** the loss function?

Loss Functions

- Per-example loss function
  - Computes how good a model is doing on a given example:
    $l(M(x), y) \geq 0$
- So many loss functions…
  - Classification: hinge loss, log-loss, …
  - Regression: mean squared error, mean absolute error, robust loss, …
- In this lecture, we stick to distribution-based loss functions.

Probability in 5 minutes – (1)

- An "event set" Ω contains all possible events: $\Omega = \{e_1, e_2, \ldots, e_D\}$
  - Discrete: when there are a finite number of events $|\Omega| < \infty$
  - Continuous: when there are infinitely many events $|\Omega| = \infty$
- A "random variable" X could take any one of these events: $X \in \Omega$
- A probability of an event: $p(X = e_i)$
  - How likely would the *i*-th event happen?
  - How often has the *i*-th event occur relative to the other events?
- Properties
  1. Non-negative: $p(X = e_i) \geq 0$
  2. Unit volume: $\sum_{e \in \Omega} p(X = e) = 1$

Probability in 5 minutes – (2)

- Multiple random variables: consider two here - X, Y
- A joint probability $p(Y = e_j^Y, X = e_i^X)$
  - How likely would e_j^Y and e_i^X happen together?
- A conditional probability $p(Y = e_j^Y | X = e_i^X)$
  - Given e_i^X, how likely would e_j^Y happen?
  - The chance of both happening together divided by that of e_i^X happening regardless of whether e_j^Y happened:

$$p(Y|X) = \frac{p(X,Y)}{p(X)} \iff p(X,Y) = p(Y|X)p(X)$$

- Probability function $p(X)$ returns a probability of X

Probability in 5 minutes – (3)

- Multiple random variables: consider two here - X, Y
- A joint probability $p(Y = e_j^Y, X = e_i^X)$
  - How likely would e_j^Y and e_i^X happen together?
- A marginal probability $p(Y = e_j^Y)$
  - Regardless of what happens to X, how likely is e_j^Y?

$$p(Y = e_j^Y) = \sum_{e \in \Omega_X} p(Y = e_j^Y, X = e)$$

A Neural network computes a conditional distribution

- Supervised learning: what is y given x?

$$f_\theta(x) = ?$$

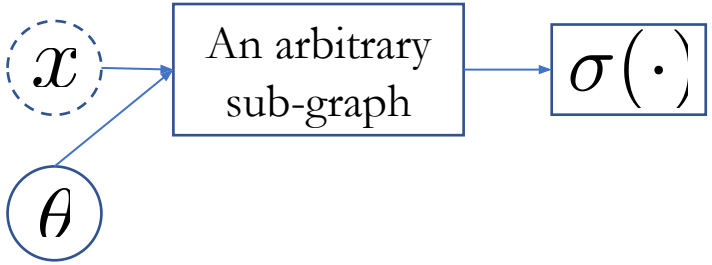
- In other words, how probable is a certain value y' of y given x?

$$p(y = y'|x) = ?$$

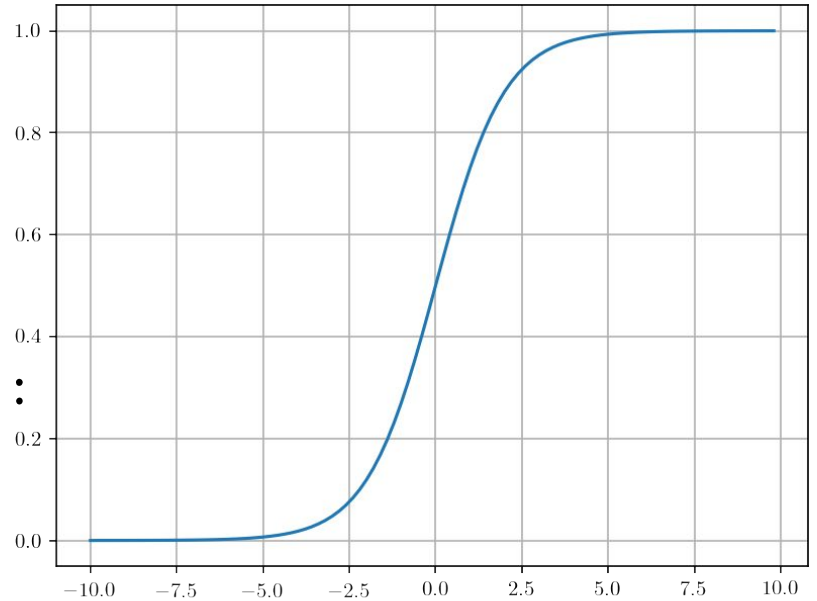
- What kind of distributions?
  - Binary classification: Bernoulli distribution
  - Multiclass classification: Categorical distribution
  - Linear regression: Gaussian distribution
  - Multimodal linear regression: Mixture of Gaussians

Important distributions – Bernoulli

- How probable is a certain value y' of y given x? $p(y = y'|x) = ?$
- Binary classification: Bernoulli distribution $\mathcal{B}(\mu)$
  - Probability: $p(y|x) = \mu^y(1-\mu)^{1-y}$, where $y \in \{0, 1\}$
  - Fully characterized by $\mu \in [0, 1]$.
  - A neural network then should turn the input x into μ

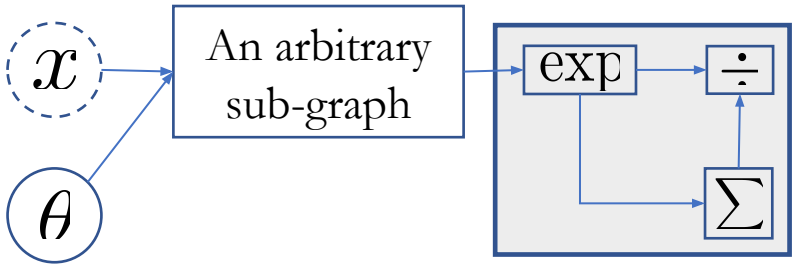


using a sigmoid function $\sigma(a) = \dfrac{1}{1+\exp(-a)}$:



Important distributions – Categorical

- How probable is a certain value y' of y given x? $p(y = y'|x) = ?$
- Multi-class classification: Categorical distribution $\mathcal{C}(\{\mu_1, \mu_2, \ldots, \mu_C\})$
  - Probability: $p(y = v|x) = \mu_v$, where $\sum_{v=1} \mu_v = 1$
  - Fully characterized by $\{\mu_1, \mu_2, \ldots, \mu_C\}$.
  - A neural network then should turn the input x into a vector $\mu = \begin{bmatrix} \mu_1 \\ \mu_2 \\ \vdots \\ \mu_C \end{bmatrix}$



using a **softmax** function: $\text{softmax}(a) = \frac{1}{\sum_{v=1}^{C} \exp(a_v)} \exp(a)$.

Important distributions – Gaussian

- How probable is a certain value y' of y given x? $p(y = y'|x) = ?$
- Regression: Gaussian distribution $\mathcal{N}(\mu, \mathbb{I})$ with an identity covariance
  - Probability: $p(y|x) = \frac{1}{Z} \exp(-\frac{1}{2}(y-\mu)^\top (y-\mu))$
  - Fully characterized by $\mu \in \mathbb{R}^q$.
  - A neural network then should turn the input x into a vector μ.
  - Can be done trivially by affine transformation.

Loss Function – negative log-probability

- Once a neural network outputs a conditional distribution $p_\theta(y|x)$, a natural way to define a loss function arises.
- Make sure training data is maximally likely:
  - Equiv. to making sure each and every training example is maximally likely.

$$\arg\max_\theta \log p_\theta(D) = \arg\max_\theta \sum_{n=1}^{N} \log p_\theta(y_n|x_n)$$

  - Why *log*? – many reasons… but out of the lecture's scope.
- Equivalently, we want to minimize the *negative* log-probability.
  - A loss function is the sum of negative log-probabilities of correct answers.

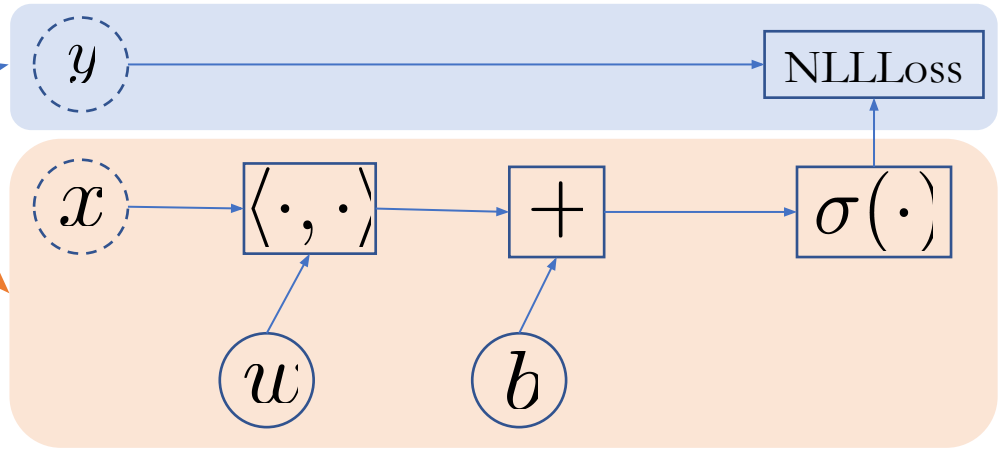
$$L(\theta) = \sum_{n=1}^{N} l(M_\theta(x_n), y_n) = -\sum_{n=1}^{N} \log p_\theta(y_n|x_n)$$

Loss Function – negative log-probability

- Once a neural network outputs a conditional distribution $p_\theta(y|x)$, a natural way to define a loss function arises.
- Practical implications
  - An OP node: negative log-probability (e.g., NLLLoss in PyTorch)
    - Inputs: the conditional distribution and the correct output
    - Output: the negative log-probability (a scalar)

Loss Function – negative log-probability

- Once a neural network outputs a conditional distribution $p_\theta(y|x)$, a natural way to define a loss function arises.
- Logistic regression
  - Computes a Bernoulli distribution
  - Computes a negative log-probability
  - All in **one directed acyclic graph**
- Forward computation
  - Computes the conditional distribution, and
  - Computes the per-example loss



Supervised Learning

- Three points to consider both in research and in practice
  1. How do we decide/design a **hypothesis set**?
  2. How do we decide a **loss function**?
  3. How do we **optimize** the loss function?

Loss Minimization

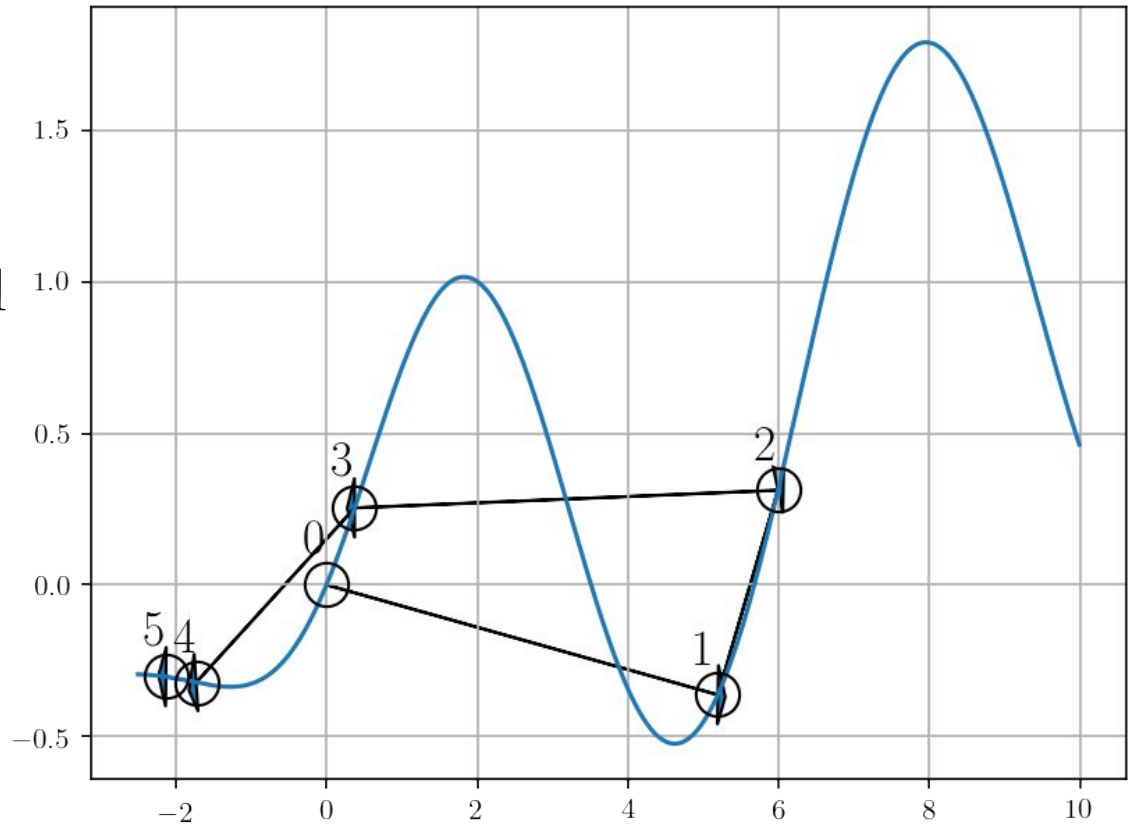
- What we now know
  1. How to build a neural network with an arbitrary architecture.
  2. How to define a per-example loss as a negative log-probability.
  3. Define a single directed acyclic graph containing both.
- What we now need to know
  1. Choose an optimization algorithm.
  2. How to use the optimization algorithm to estimate parameters θ.

Local, iterative optimization

- An arbitrary function $L : \mathbb{R}^d \to \mathbb{R}$
- Given the current value θ_C, how should I move to minimize L?
- Random guided search
  - Stochastically perturb θ_C: $\theta_k = \theta + \epsilon_k$, where $\epsilon_k \sim \mathcal{N}(0, s^2\mathbf{1})$
  - Test each perturbed point $L(\theta_k)$
  - Find the best perturbed point $\theta_1 = \arg\min_{\theta_k} L(\theta_k)$
  - Repeat this until no improvement could be made.
- Applicable to any arbitrary loss function and neural network.
- Inefficient in the high-dimensional parameter space: large d.

Local, iterative optimization

- An arbitrary function $L : \mathbb{R}^d \rightarrow \mathbb{R}$
- Given the current value θ_0, how should I move to minimize L?
- Random guided search
  - Applicable to any arbitrary loss function and neural network.
  - Inefficient in the high-dimensional parameter space



Gradient-based optimization

- A **continuous**, **differentiable*** function $L : \mathbb{R}^d \to \mathbb{R}$
- Given the current value θ_0, how should I move to minimize L?
- Gradient descent
  - The negative gradient of the function: $-\nabla L(\theta_0)$
  - This is only valid in a local neighbourhood of θ_0: take a very small step!

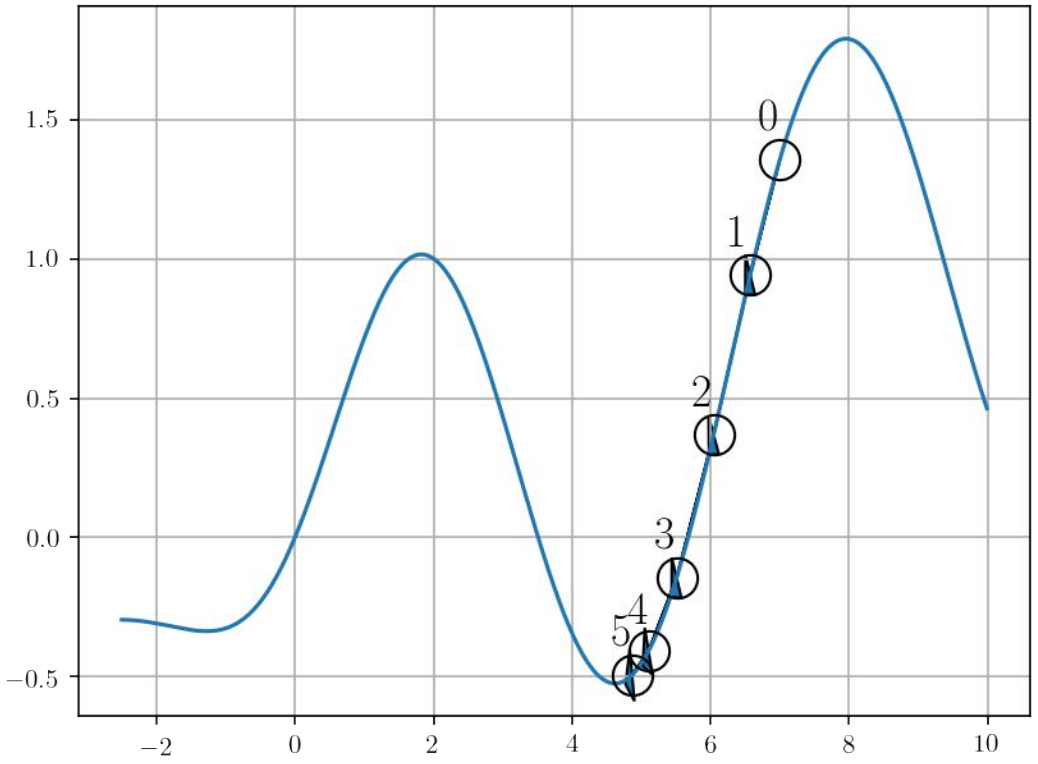
$$\theta = \theta_0 - \eta \nabla L(\theta_0)$$

- Efficient and effective even in the high dimensional space.
  - Can be improved with the second-order information (Hessian and/or FIM)

* Almost everywhere, but not necessarily everywhere

Gradient-based optimization

- A **continuous**, **differentiable** function $L : \mathbb{R}^d \to \mathbb{R}$
- Given the current value θ_0, how should I move to minimize L?
- Gradient descent
  - Efficient and effective even in the high dimensional space.
  - Learning rate must be carefully selected and annealed over time.



Backward Computation – Backpropagation

- How do we compute the gradient of the loss function?

1. Manual derivation
   - Relatively doable when the DAG is small and simple.
   - When the DAG is larger and complicated, too much hassle.
2. Automatic differentiation (autograd)
   - Use the chain rule of derivatives

$$\frac{\partial(f \circ g)}{\partial x} = \frac{\partial f}{\partial g}\frac{\partial g}{\partial x}$$

   - The DAG is nothing but a composition of (mostly) differentiable functions.
   - Automatically apply the chain rule of derivatives.

Backward Computation – Backpropagation

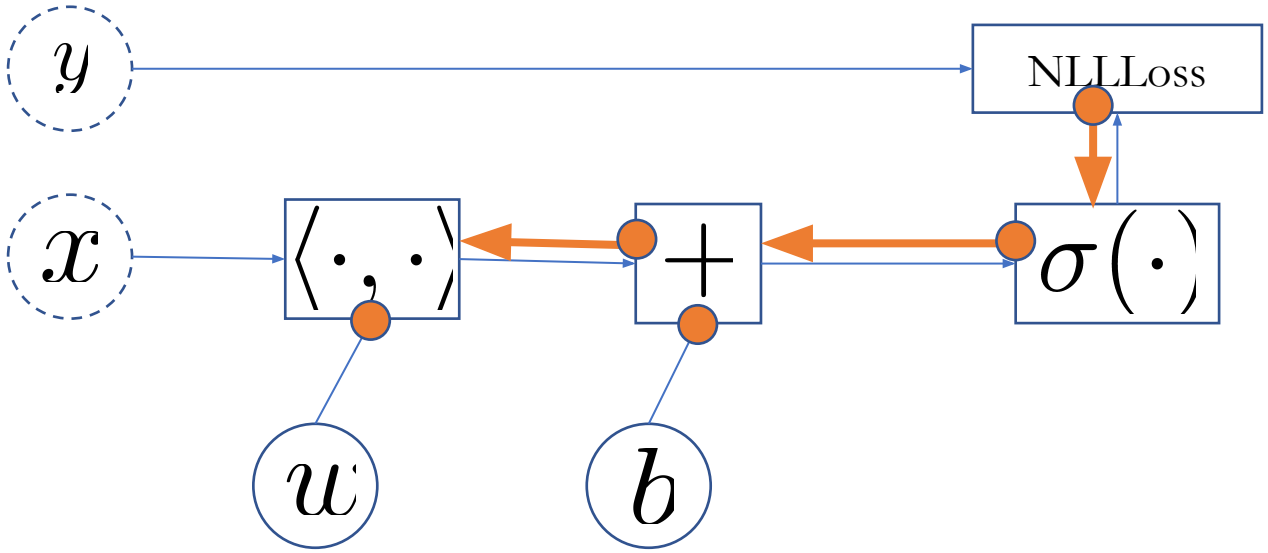
- Automatic differentiation (autograd)
  1. Implement the Jacobian-vector product of each OP node:

$$\begin{bmatrix} \frac{\partial L}{\partial x_1} \\ \vdots \\ \frac{\partial L}{\partial x_d} \end{bmatrix} = \begin{bmatrix} \frac{\partial F_1}{\partial x_1} & \cdots & \frac{\partial F_{d'}}{\partial x_1} \\ \vdots & \ddots & \vdots \\ \frac{\partial F_1}{\partial x_d} & \cdots & \frac{\partial F_{d'}}{\partial x_d} \end{bmatrix} \begin{bmatrix} \frac{\partial L}{\partial F_1} \\ \vdots \\ \frac{\partial L}{\partial F_{d'}} \end{bmatrix}$$

  - Can be implemented efficiently without explicitly computing the Jacobian.
  - The same implementation can be reused every time the OP node is called.

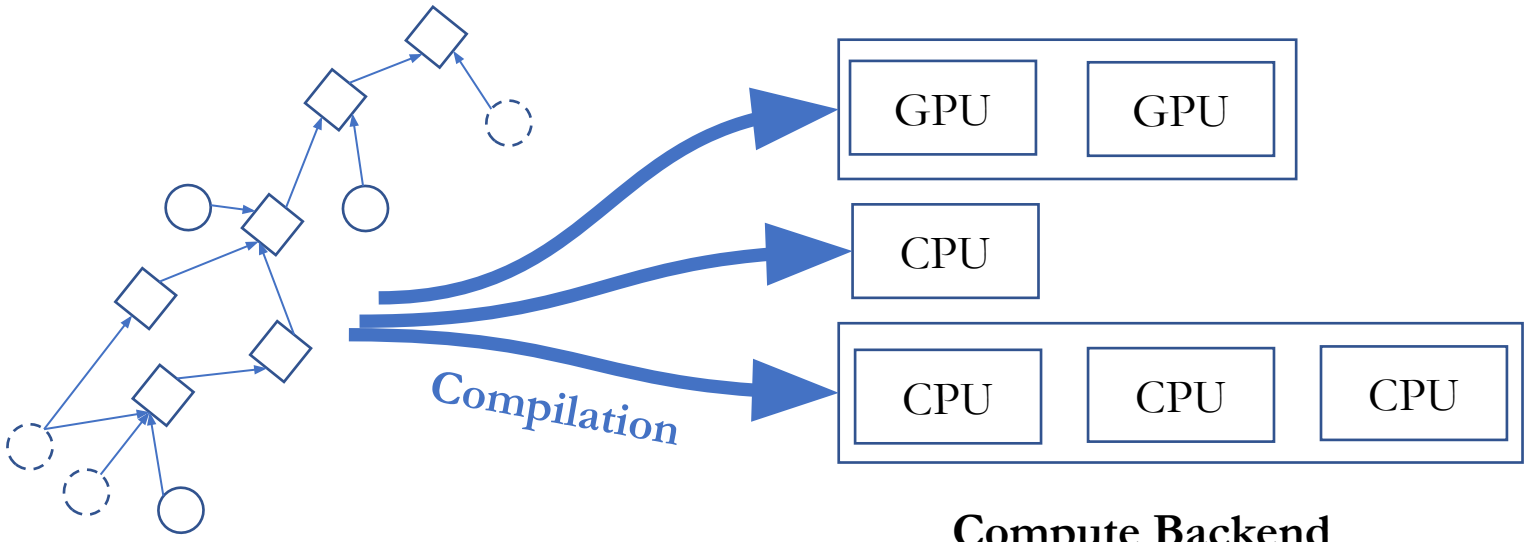
Backward Computation – Backpropagation

- Automatic differentiation (autograd)
  2. Reverse-sweep the DAG starting from the loss function node.
     - Iteratively multiplies the Jacobian of each OP node until the leaf nodes of the parameters.
     - As expensive as forward computation with a constant overhead: O(N), where N: # of nodes.



Backward Computation – Backpropagation

- Practical Implications – Automatic differentiation (autograd)
  - Unless a complete new OP is introduced, no need to manually derive the gradient
  - Nice de-coupling of specification (front-end) and implementation (back-end)
    1. [Front-end] Design a neural network by creating a DAG.
    2. [Back-end] The DAG is "compiled" into an efficient code for a target compute device.



Gradient-based Optimization

- Backpropagation gives us the gradient of the loss function w.r.t. θ
- Readily used by off-the-shelf gradient-based optimizers
  - Gradient descent, L-BFGS, Conjugate gradient, …
  - Though, most are not applicable in a realistic neural network with 10s or 100s of millions of parameters.
- Stochastic gradient descent
  - Approximate the full loss function (the sum of per-examples losses) using only a small random subset of training examples:

$$\nabla L \approx \frac{1}{N'} \sum_{n=1}^{N'} \nabla l(M(x_{n'}), y_{n'})$$

Stochastic Gradient Descent

- Stochastic gradient descent
  - Approximate the full loss function (the sum of per-examples losses) using only a small random subset of training examples:

$$\nabla L \approx \frac{1}{N'} \sum_{n=1}^{N'} \nabla l(M(x_{n'}), y_{n'})$$

  - Unbiased estimate of the full gradient.*
  - Learning rate must be annealed appropriately.
  - Extremely efficient *de facto* standard practice.

* Under certain conditions

Stochastic Gradient Descent

- Stochastic gradient descent in practice
  1. Grab a random subset of M training examples*
     $D' = \{(x_1, y_1), \ldots, (x_{N'}, y_{N'})\}$
  2. Compute the minibatch gradient
     $$\nabla L \approx \frac{1}{N'} \sum_{n=1}^{N'} \nabla l(M(x_{n'}), y_{n'})$$
  3. Update the parameters
     $\theta \leftarrow \theta + \eta \nabla L(\theta; D')$
  4. Repeat until the validation loss stops improving.⋆

* In practice, sample without replacement until the training set is exhausted (one epoch).

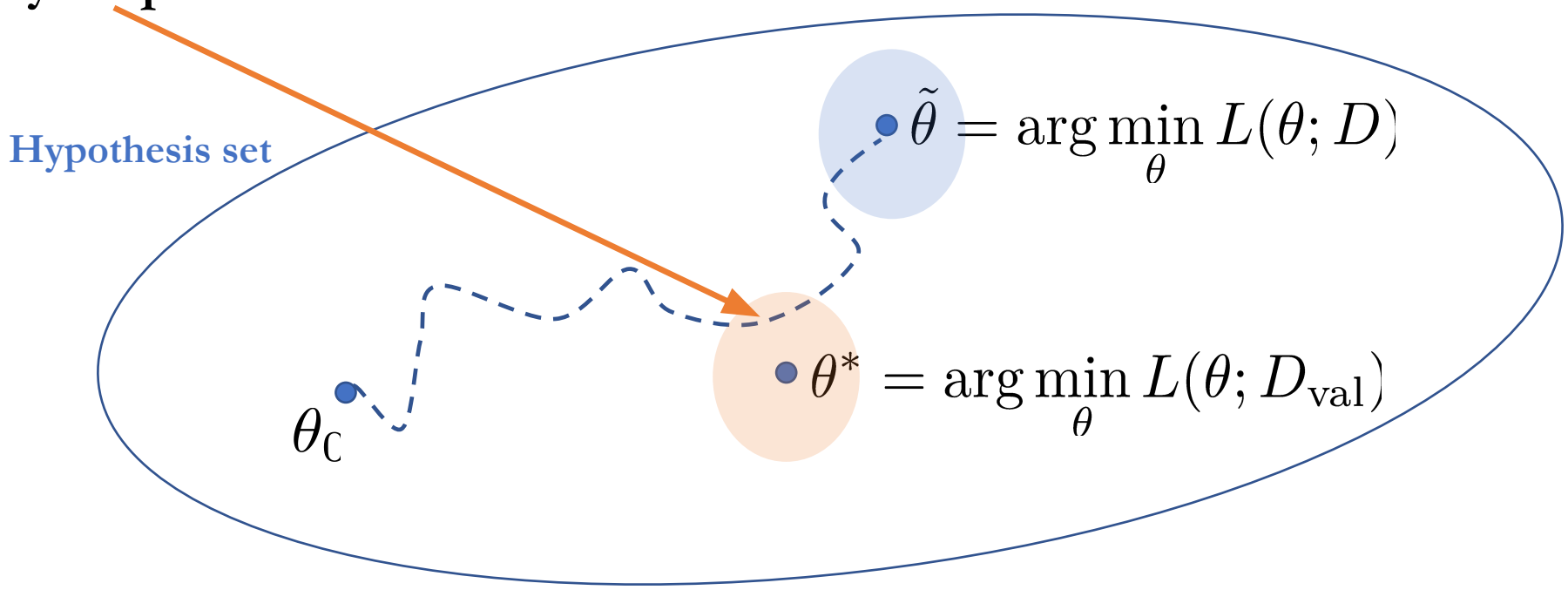
⋆ This is called early-stopping which prevents the neural network from overfitting to training examples.

Stochastic Gradient Descent – Early Stopping

- Stochastic gradient descent in practice
  1. Grab a random subset of *M* training examples
  2. Compute the minibatch gradient
  3. Update the parameters
  4. **Repeat until the validation loss stops improving.**
- An efficient way to prevent overfitting
  - Overfitting: the training loss is low, but the validation loss is not.
  - The most serious problem in statistical machine learning.
  - Early-stop based on the validation loss

Stochastic Gradient Descent – Early Stopping

- An efficient way to prevent overfitting
  - Overfitting: the training loss is low, but the validation loss is not.
  - The most serious problem in statistical machine learning.
  - **Early-stop** based on the validation loss



Stochastic Gradient Descent – Adaptive Learning Rate

- Stochastic gradient descent in practice
  1. Grab a random subset of *M* training examples $D' = \{(x_1, y_1), \ldots, (x_{N'}, y_{N'})\}$
  2. Compute the minibatch gradient
  3. Update the per-parameter learning rate η_θ
  4. Update the parameters

$$\theta \leftarrow \theta - \eta_\theta \frac{\partial L'}{\partial \theta}$$

  5. Repeat until the validation loss stops improving.
- Adaptive learning rate: Adam [Kingma&Ba, 2015], Adadelta [Zeiler, 2015], and many more…
  - Approximately re-scale parameters to improve the conditioning of the Hessian.

Supervised Learning with Neural Networks

1. How do we decide/design a **hypothesis set**?
   - Design a network architecture as a directed acyclic graph
2. How do we decide a **loss function**?
   - Frame the problem as a conditional distribution modelling
   - The per-example loss function is a negative log-probability of a correct answer
3. How do we **optimize** the loss function?
   - Automatic backpropagation: no manual gradient derivation
   - Stochastic gradient descent with early stopping [and adaptive learning rate]

Language modeling as supervised learning

On the boundary between unsupervised and supervised learning

Language Modelling

- Input: a sentence
- Output: the probability of the input sentence
- A language model captures the distribution over all possible sentences.
  $p(X) = p((x_1, x_2, \ldots, x_T))$
- It is *unsupervised learning*.
  - We will however turn the problem into a *sequence of supervised learning*.

Autoregressive language modelling

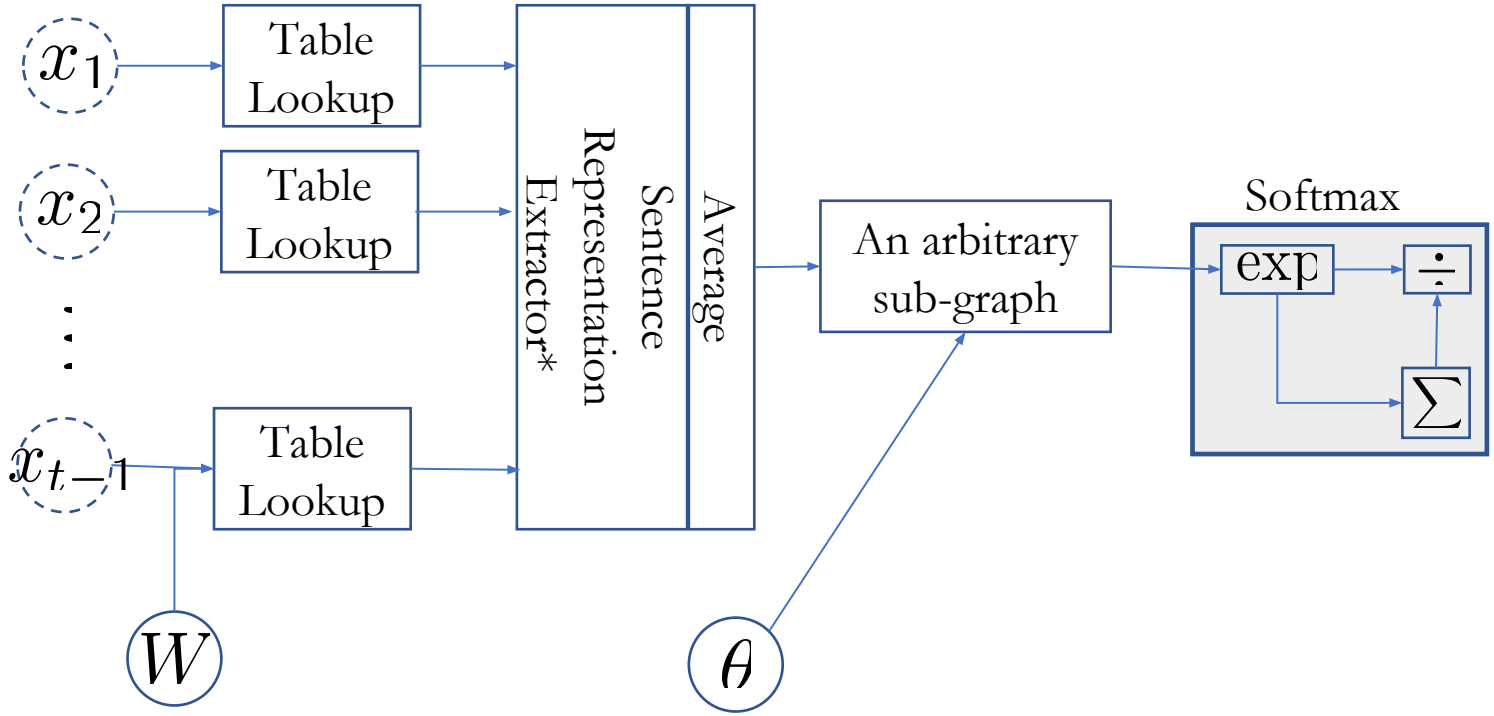
- Autoregressive sequence modelling
  - The distribution over the next token is based on all the previous tokens.
    $p(X) = p(x_1)p(x_2|x_1) \cdots p(x_T|x_1, \ldots, x_{T-1})$
  - This equality holds exactly due to the def. of conditional distribution.
- Unsupervised learning becomes a set of supervised problems.
  - Each conditional is a neural network classifier.
  - Input is all the previous tokens (a partial sentence).
  - Output is the distribution over all possible next tokens (classes).
  - It is a **text classification** problem.

Autoregressive language modelling

- Autoregressive sequence modelling
  - The distribution over the next token is based on all the previous tokens.

$$p(X) = p(x_1)p(x_2|x_1)\cdots p(x_T|x_1,\ldots,x_{T-1})$$

- Each conditional is a sentence classifier:

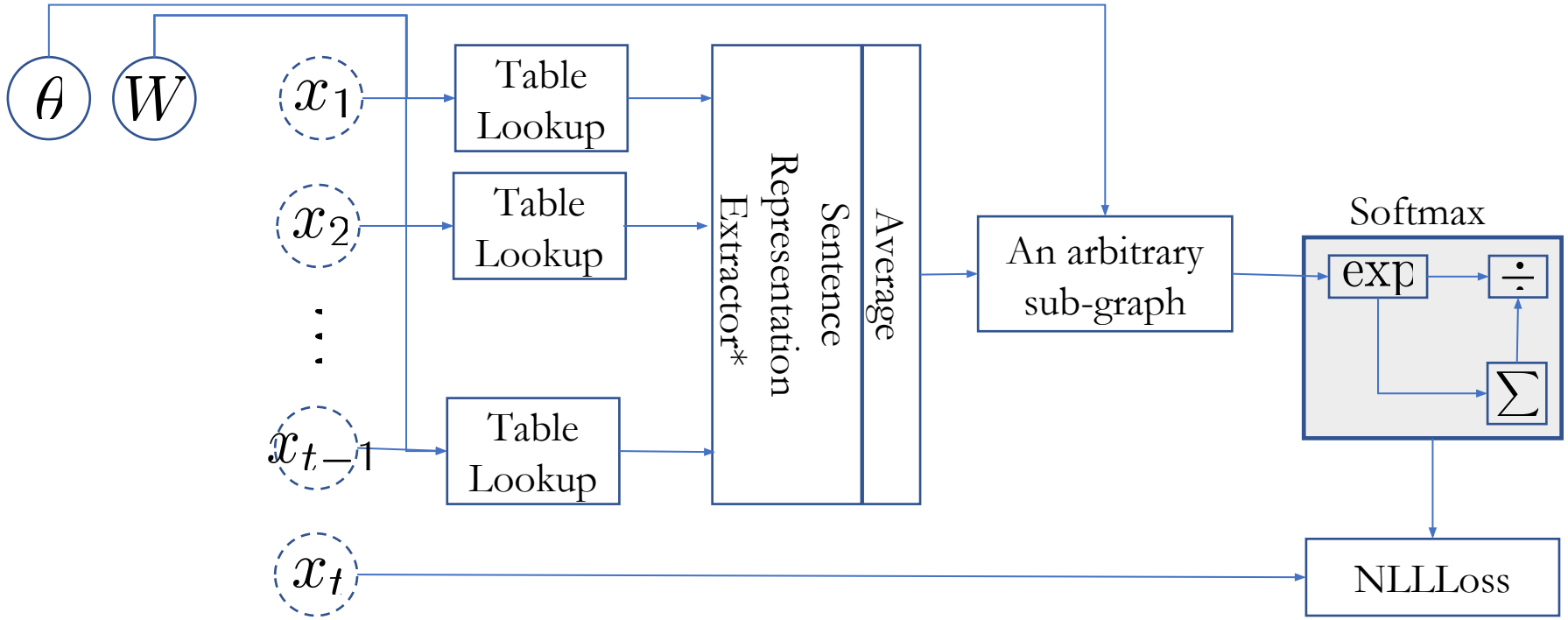


* See Lecture 2.

Autoregressive language modelling

- Autoregressive sequence modelling $p(X) = \prod_{t=1}^{T} p(x_t|x_{<t})$
- Loss function: the sum of negative log-probabilities

$$\log p_\theta(X) = \sum_{n=1}^{N} \sum_{t=1}^{T} \log p_\theta(x_t|x_{<t})$$



Scoring a sentence

- Autoregressive sequence modelling
  - The distribution over the next token is based on all the previous tokens.
    $p(X) = p(x_1)p(x_2|x_1)\cdots p(x_T|x_1,\ldots,x_{T-1})$
- A natural way to score a sentence:
  - In Korea, more than half of residents speak Korean.
  - "In" is a reasonable token to start a sentence.
  - "Korea" is pretty likely given "In"
  - "more" is okay token to follow "In Korea"
  - "than" is very likely after "In Korea, more"
  - "half" is also very likely after "In Korea, more than"

⋮

- Sum all these scores and get the sentence score.

Scoring a sentence

- Autoregressive sequence modelling
  - The distribution over the next token is based on all the previous tokens.
    $p(X) = p(x_1)p(x_2|x_1)\cdots p(x_T|x_1,\ldots,x_{T-1})$
- A natural way to score a sentence:
  - "In Korea, more than half of residents speak Korean."
    vs.
    "In Korea, more than half of residents speak Finnish."
  - The former is more likely (=higher probability) than the latter.
- This is precisely what NLLLoss computes over the sentence.

N-Gram Language Models

- Let's back up a little…
- What would we do *without* a neural network?
- Assume a Markovian property

$$p(X) = \prod_{t=1}^{T} p(x_t|x_{<t}) \approx \prod_{t=1}^{T} p(x_t|x_{t-n}, \ldots, x_{t-1})$$

- This turned out to be crucial, and we will discuss why shortly.

N-Gram Language Models

$$p(X) = \prod_{t=1}^{T} p(x_t|x_{<t}) \approx \prod_{t=1}^{T} p(x_t|x_{t-n}, \ldots, x_{t-1})$$

- We need to estimate n-gram probabilities: $p(x|x_{-N}, x_{-N+1}, \ldots, x_{-1})$
- Recall the def. of conditional and marginal probabilities:

$$p(x|x_{-N}, x_{-N+1}, \ldots, x_{-1}) = \frac{p(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)}{p(x_{-N}, x_{-N+1}, \ldots, x_{-1})}$$

$$= \frac{p(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)}{\sum_{x \in V} p(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)}$$

  - V : all possible tokens (=vocabulary)

N-Gram Language Models

- We need to estimate *n*-gram probabilities:

$$p(x|x_{-N}, x_{-N+1}, \ldots, x_{-1}) = \frac{p(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)}{\sum_{x \in V} p(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)}$$

- How do we estimate the probability?
  - I want to estimate the probability of my distorted coin landing head.
  - **M**aximum **l**ikelihood **e**stimation (MLE):
    toss the coin a lot and look at how often it lands heads.

Data Collection Estimation

N-Gram Language Models

- We need to estimate *n*-gram probabilities:

$$p(x|x_{-N}, x_{-N+1}, \ldots, x_{-1}) = \frac{p(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)}{p(x_{-N}, x_{-N+1}, \ldots, x_{-1})}$$

- Data: all the documents or sentences you can collect
  - e.g., Wikipedia, news articles, tweets, …
- Estimation:
  1. Count the # of occurrences for the *n*-gram $(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)$
  2. Count the #'s of occurrences for all the *n*-grams of the form: $(x_{-N}, x_{-N+1}, \ldots, x_{-1}, ?)$

N-Gram Language Models

- We need to estimate *n*-gram probabilities:

$$p(x|x_{-N}, x_{-N+1}, \ldots, x_{-1}) = \frac{p(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)}{p(x_{-N}, x_{-N+1}, \ldots, x_{-1})}$$

- Estimation:

$$p(x|x_{-N}, x_{-N+1}, \ldots, x_{-1}) = \frac{p(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)}{\sum_{x \in V} p(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)}$$

$$\approx \frac{c(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)}{\sum_{x' \in V} c(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x')}$$

- *Do you see why this makes sense?*

N-Gram Language Models

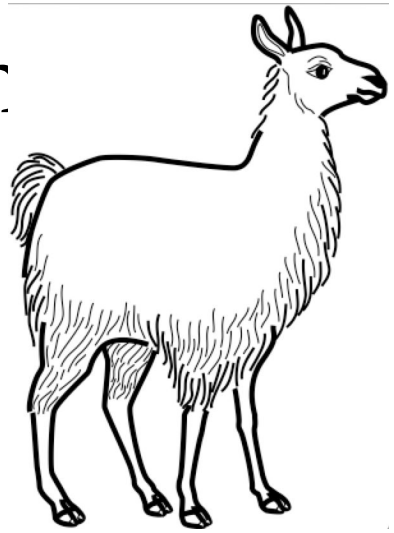
- We need to estimate n-gram probabilities:

$$p(x|x_{-N}, x_{-N+1}, \ldots, x_{-1}) = \frac{p(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)}{\sum_{x \in V} p(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)}$$

$$\approx \frac{c(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x)}{\sum_{x' \in V} c(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x')}$$

- How likely is "University" given "New York"?
  - Count all "New York University"
  - Count all "New York ?": e.g., "New York State", "New York City", "New York Fire", "New York Police", "New York Bridges", …
  - How often "New York University" happens among these?

N-Gram Language Models – Two problem



1. Data sparsity: lack of generalization
   - What happens "one" n-gram never happens?

$$p(\text{a lion is chasing a llama}) = p(\text{a}) \times p(\text{lion}|\text{a}) \times p(\text{is}|\text{a lion}) \times p(\text{chasing}|\text{lion is}) \times p(\text{a}|\text{is chasing}) \times \underbrace{p(\text{llama}|\text{chasing a})}_{=0} = 0$$

2. Inability to capture long-term dependencies
   - Each conditional only considers a small window of size *n*.
   - Consider "*the same **stump** which had impaled the car of many a guest in the past thirty years and which he refused to have **removed**'*
   - It is impossible to tell "removed" is likely by looking at the four preceding tokens.

Traditional Solutions

1. Data Sparsity
   - Smoothing: add a small constant to avoid 0.

$$p(x|x_{-N}, x_{-N+1}, \ldots, x_{-1}) \approx \frac{c(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x) + \epsilon}{\epsilon|V| + \sum_{x' \in V} c(x_{-N}, x_{-N+1}, \ldots, x_{-1}, x')}$$

   - Backoff: try a shorter window.

$$c(x_{-N}, \ldots, x) = \begin{cases} \alpha c(x_{-N+1}, \ldots, x) + \beta, & \text{if } c(x_{-N}, \ldots, x) = 0 \\ c(x_{-N}, \ldots, x), & \text{otherwise} \end{cases}$$

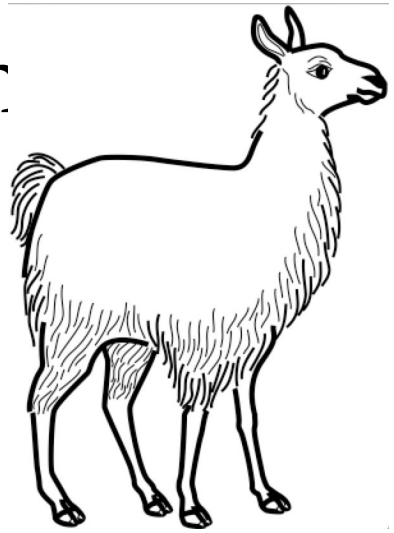
   - The most widely used approach: Kneser-Ney smoothing/backoff
   - **KenLM** implements the efficient n-gram LM model.

Traditional Solutions

2. Long-Term Dependency
   - Increase *n*: not feasible as the data sparsity worsens.
   - # of all possible *n*-grams grows exponentially w.r.t. *n*: $O(|V|^n)$
   - The data size does not grow exponentially: many never-occurring *n*-grams.

- These two problems are closely related and cannot be tackled well.
  - To capture long-term dependencies, *n* must be large.
  - To address data sparsity, *n* must be small.
  - Conflicting goals..

N-Gram Language Models – Two problem



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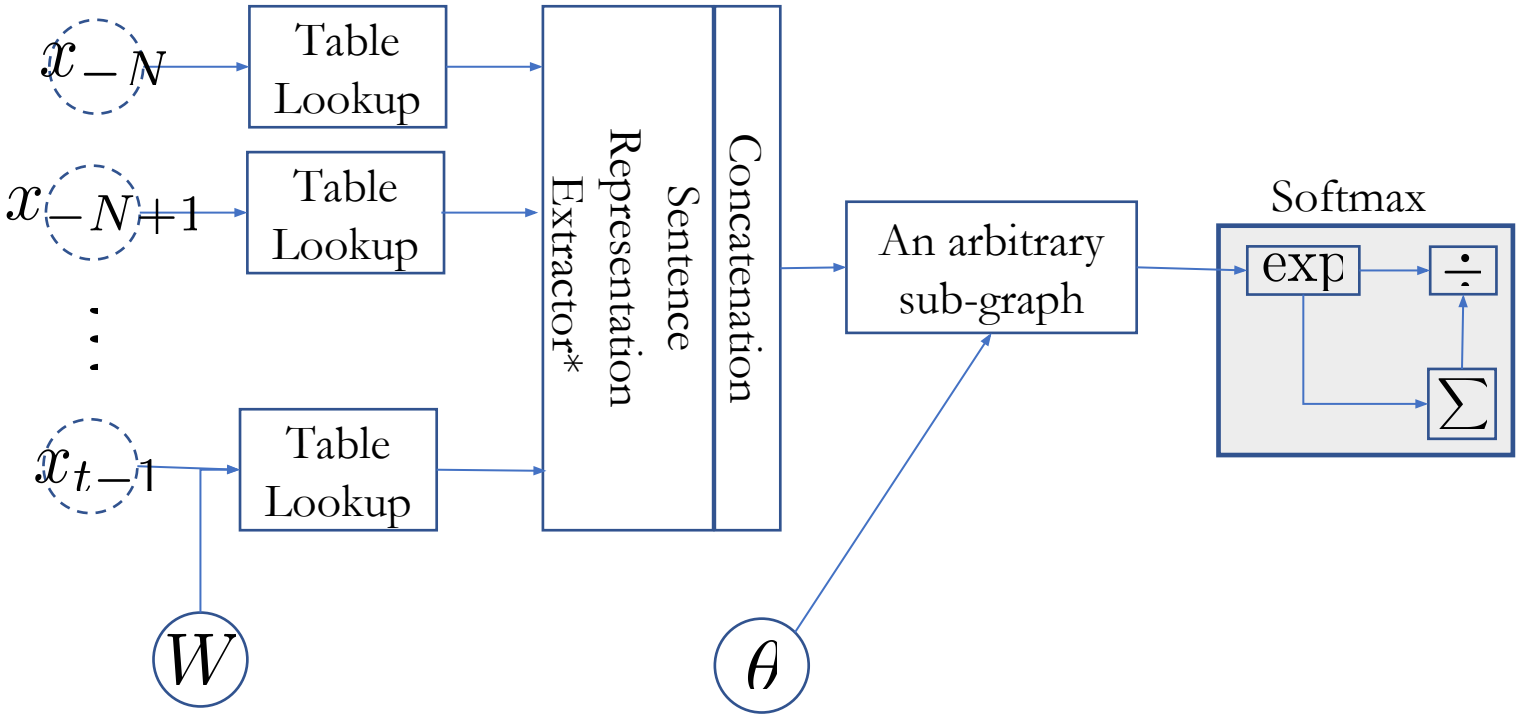
   - Each conditional only considers a small window of size *n*.
   - Consider "*the same **stump** which had impaled the car of many a guest in the past thirty years and which he refused to have **removed**'*
   - It is impossible to tell "removed" is likely by looking at the four preceding tokens.

Neural N-Gram Language Model [Bengio et al., 2001]

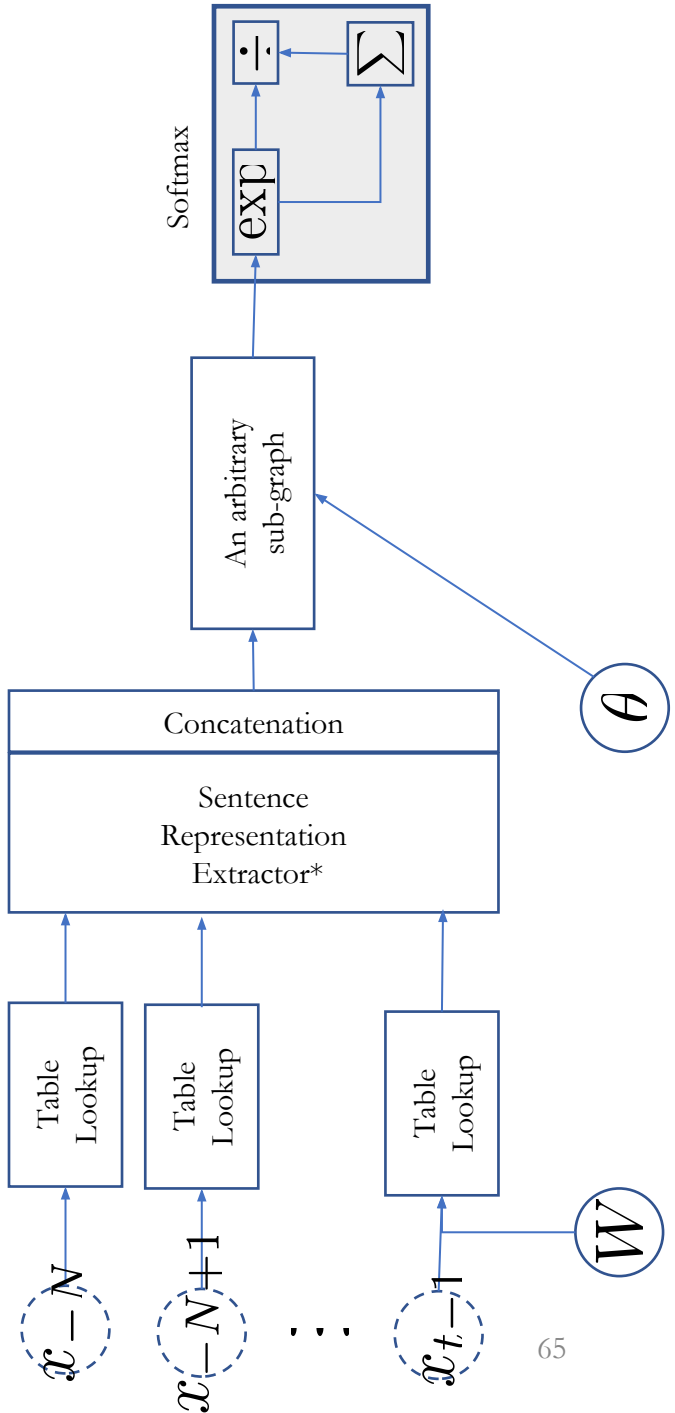
- The first extension of n-gram language models using a neural network



Neural N-Gram Language Model

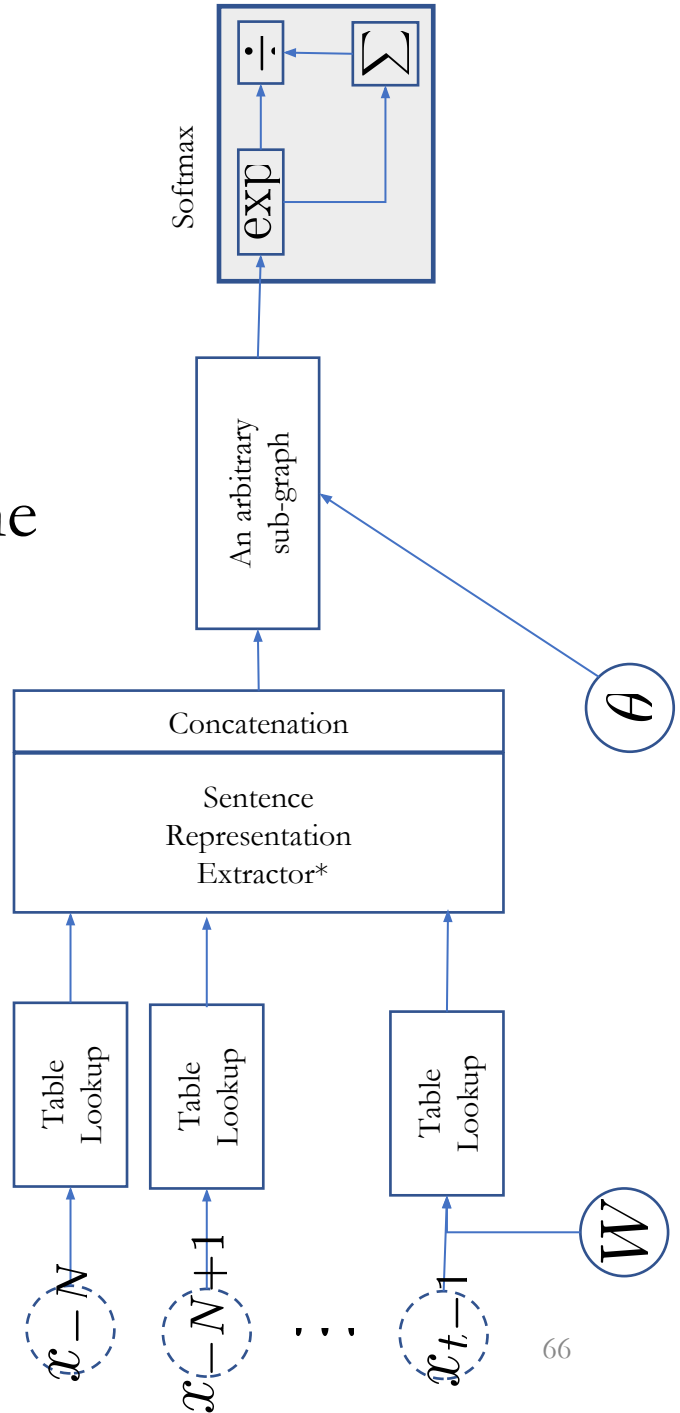
- The first neural language models
- Trained using backpropagation and SGD
- Generalizes to an unseen *n*-gram
- **Addresses the issue of data sparsity**

- *How?*



Neural N-Gram Language Model

- Why does the data sparsity happen?
- A "shallow" answer: some n-grams do not occur in the training data, while they do in the test time.
- A "slightly deeper" answer: it is difficult to impose token/phrase similarities in the discrete space.



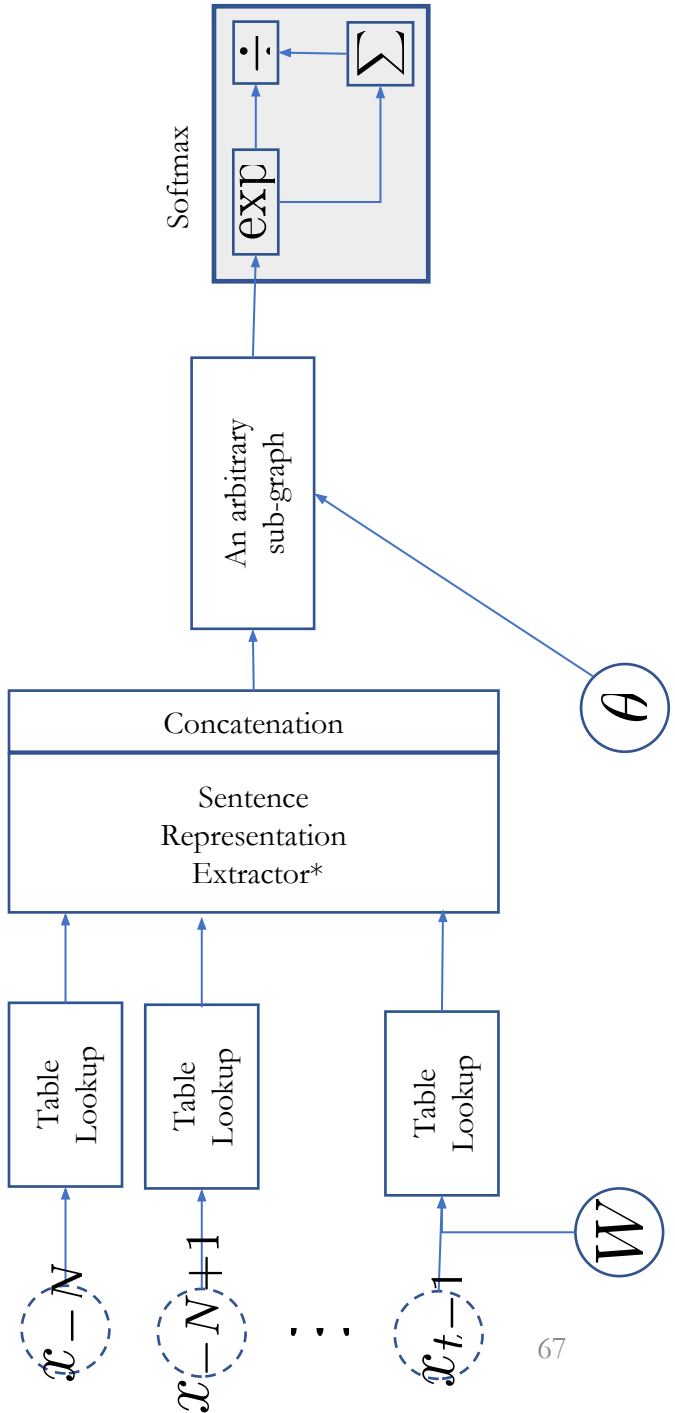
Neural N-Gram Language Model

- Why does the data sparsity happen?
- Back to the earlier example
  - Problem: $c(\text{chasing a llama}) = 0$
  - Observation: $c(\text{chasing a cat}) \gg 0$

    $c(\text{chasing a dog}) \gg 0$

    $c(\text{chasing a deer}) \gg 0$

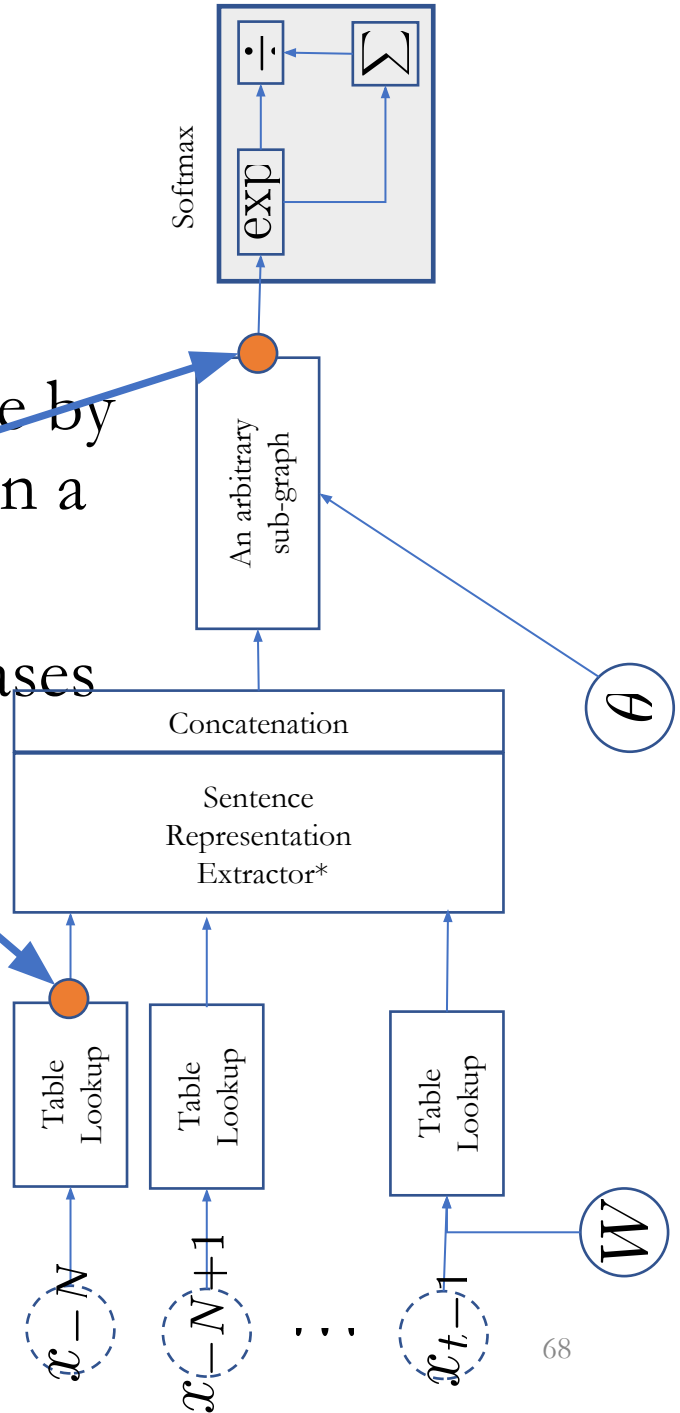
  - If the LM knew "llama" is a mammal similar to "cat", "dog" and "deer", it would be able to guess "chasing a llama" is as likely as "chasing a cat", "chasing a dog", and "chasing a deer".



Neural N-Gram Language Model

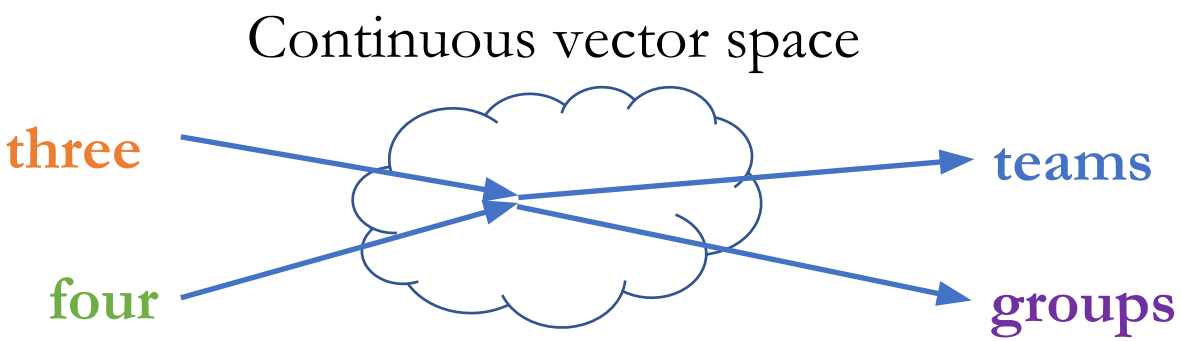
- The neural n-gram language model addresses this issue by "learning the similarities" among tokens and phrases in a "continuous vector space".
- In the "continuous vector space", similar tokens/phrases are nearby: e.g., word2vec [Mikolov et al., 2013; Pennington et al., 2014], doc2vec [Le&Mikolove, 2014], sentence-to-vec [Hill et al., 2016 and ref's therein]
- Then, similar input n-grams lead to similar output:

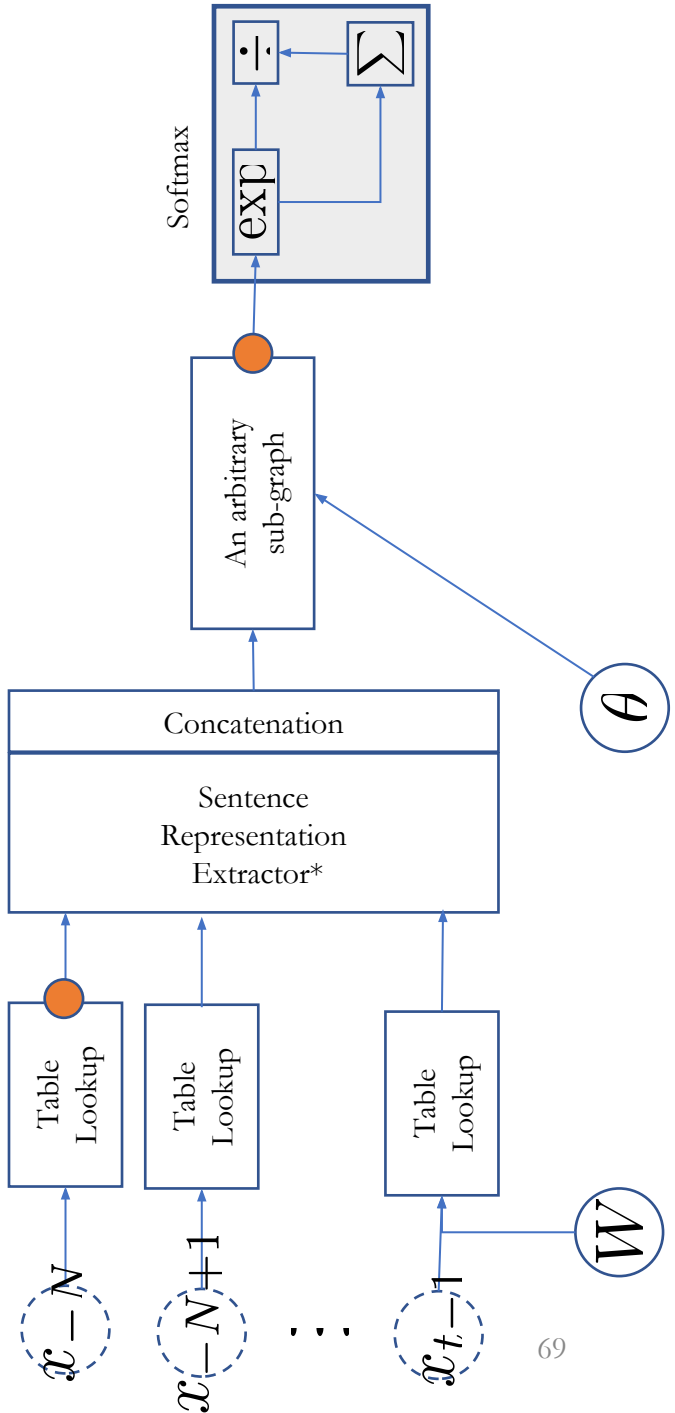
$$D(x_t|x_{t-N},\ldots,x_{t-1}\|x_t|x'_{t-N},\ldots,x'_{t-1}) < \epsilon$$



Neural N-Gram Language Model

- Training examples
  - there are **three teams** left for qualification.
  - **four teams** have passed the first round.
  - **four groups** are playing in the field.
- Q: how likely is "groups" followed by "three"?



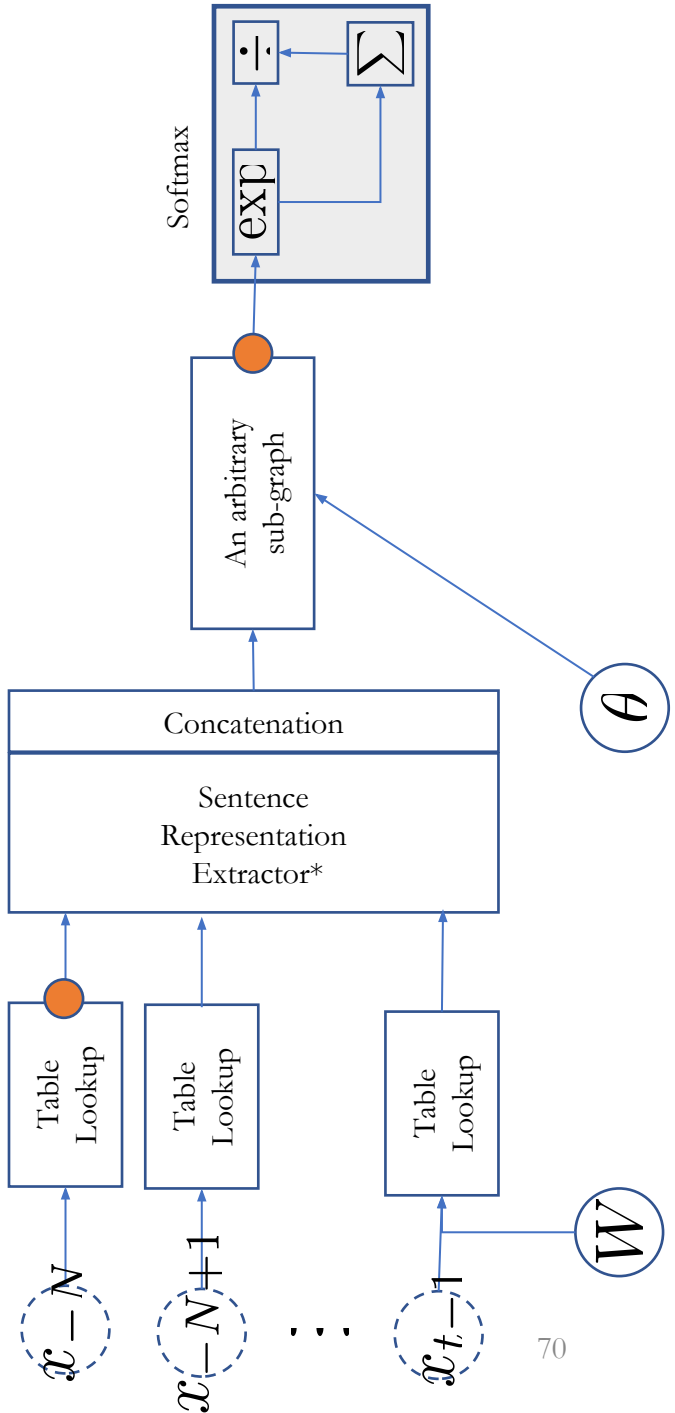


Neural N-Gram Language Model

- In practice,

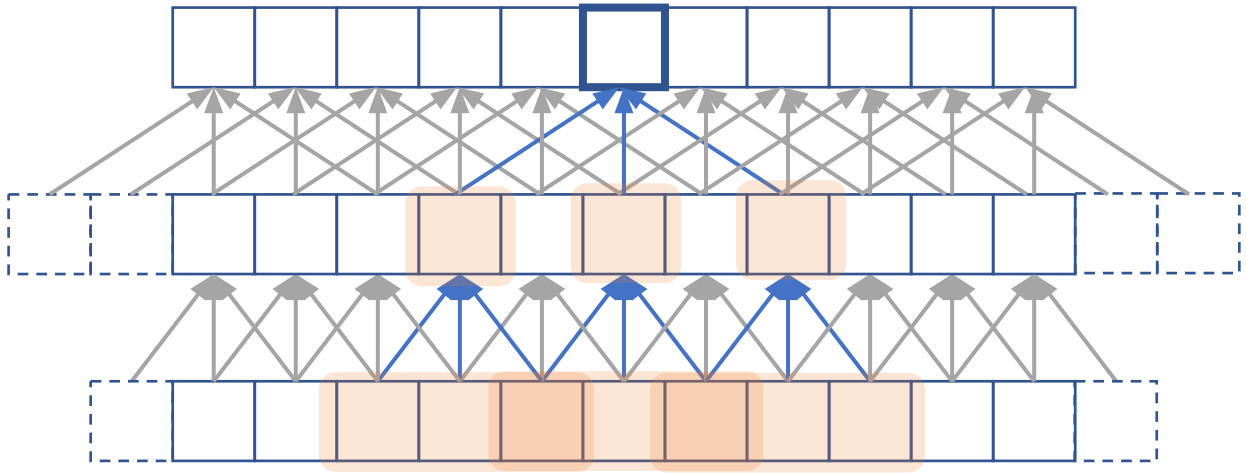
1. Collect all n-grams from the corpus.
2. Shuffle all the n-grams to build a training set
3. Train the neural n-gram language model using stochastic gradient descent on minibatches containing 100-1000 n-grams.
4. Early-stop based on the validation set.
5. Report perplexity on the test set.

$$\text{ppl} = b^{\frac{1}{|D|}\sum_{(x_1,\ldots,x_N)\in D}\log_b p(x_N|x_1,\ldots,x_{N-1})}$$



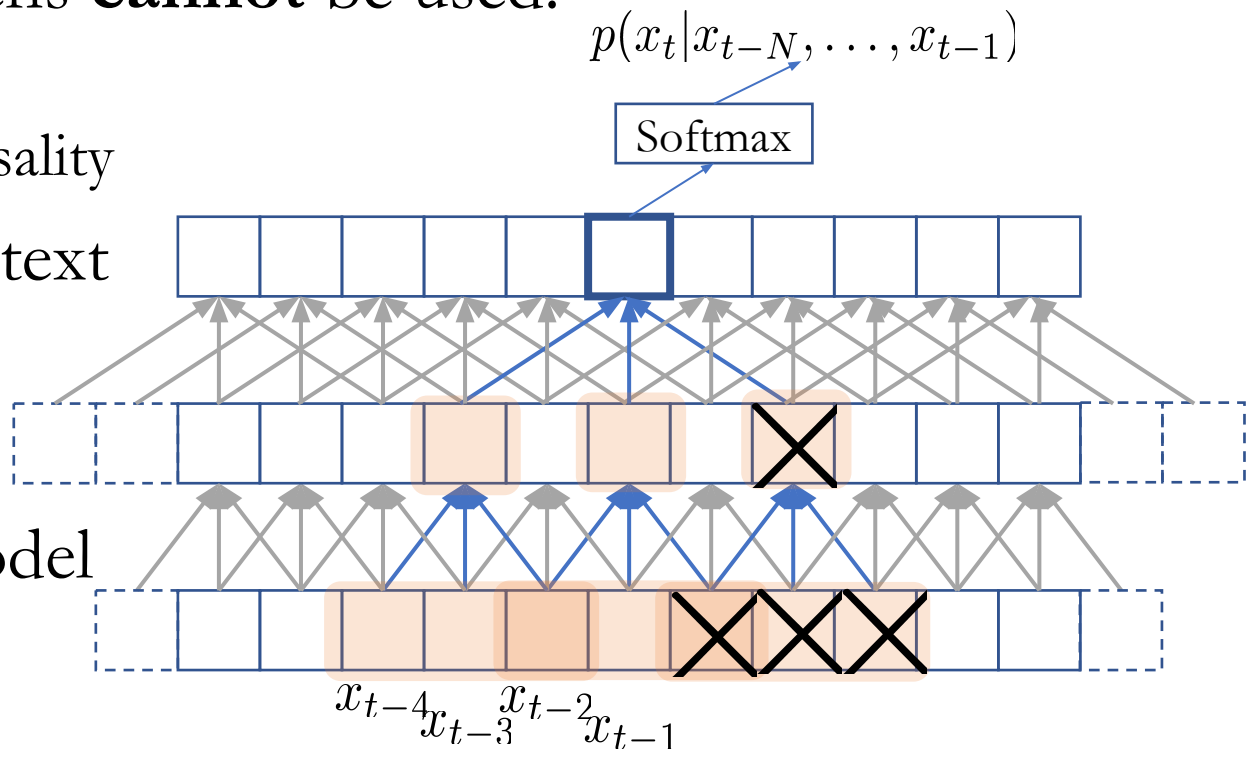
Increasing the context size – Convolutional Language Models [Kalchbrenner et al., 2015; Dauphin et al., 2016]

- Dilated convolution to rapidly increase the window size
  - Exponential-growth of the window by introducing a multiplicative factor
  - By carefully selecting the multiplicative factor, no loss in the information.



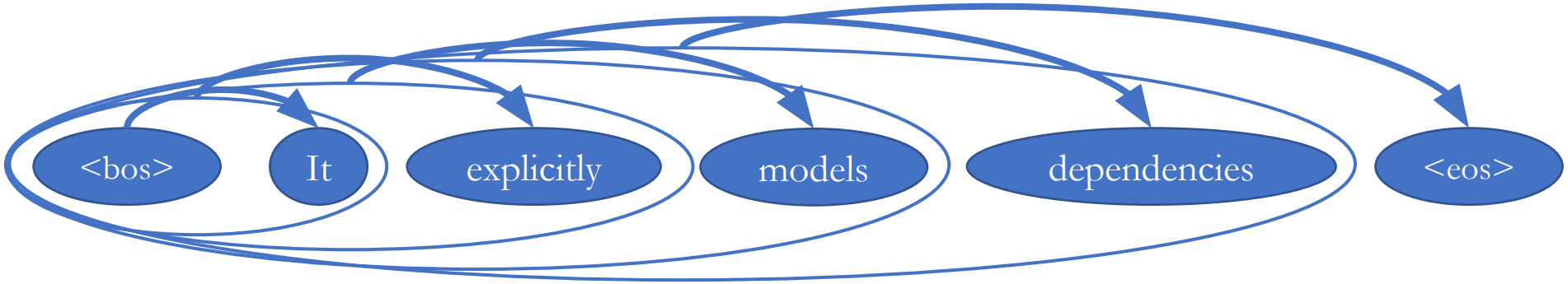
Increasing the context size – Convolutional Language Models [Kalchbrenner et al., 2015; Dauphin et al., 2016]

- Dilated convolution to rapidly increase the window size
- Causal convolution: the future tokens **cannot** be used.
  - Computation as usual: efficiency
  - Clever masking of future tokens: causality
- Efficient computation + larger context
- ByteNet [Kalchbrenner et al., 2015]
  - PixelCNN, WaveNet, …
- Gated Convolutional Language Model [Dauphin et al., 2016]



Causal sentence representation and language modelling

- Any sentence representation learning method from Lecture 2 could be used as long as it does not break the generative story:



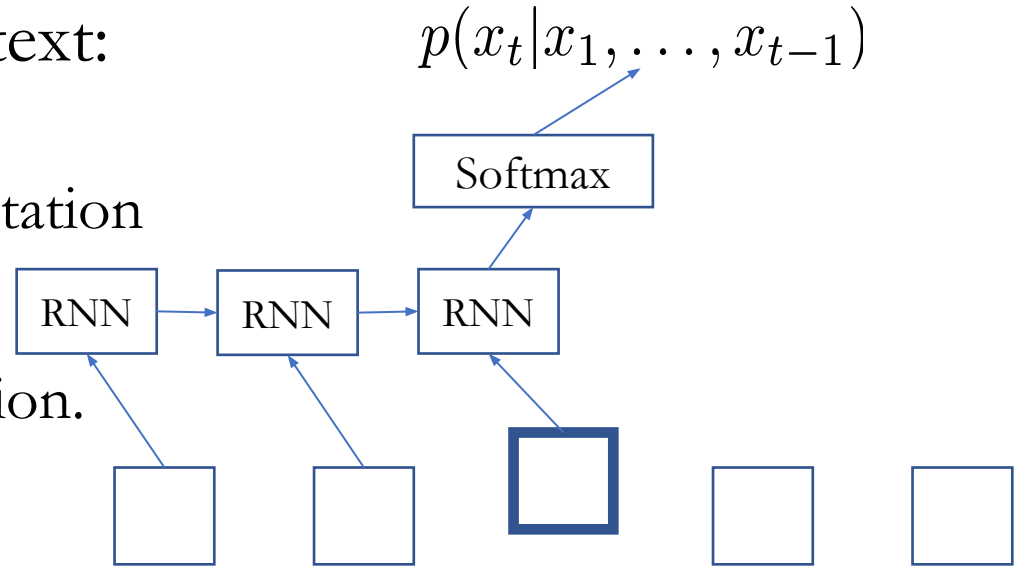
- In addition to the feedforward and convolutional n-gram language models, we can use any of the remaining sentence representation.

Infinite context $n \to \infty$ – CBoW Language Models

- Equivalent to the neural LM after replacing "concat" with "average"
  - "Averaging" allows the model to consider the infinite large context window.
- Extremely efficient, but a weak language model
  - Ignores the order of the tokens in the context windows.
    - Any language with a fixed order cannot be modelled well.
  - Averaging ignores the absolute counts, which may be important:
    - If the context window is larger, "verb" becomes less likely in SVO languages.

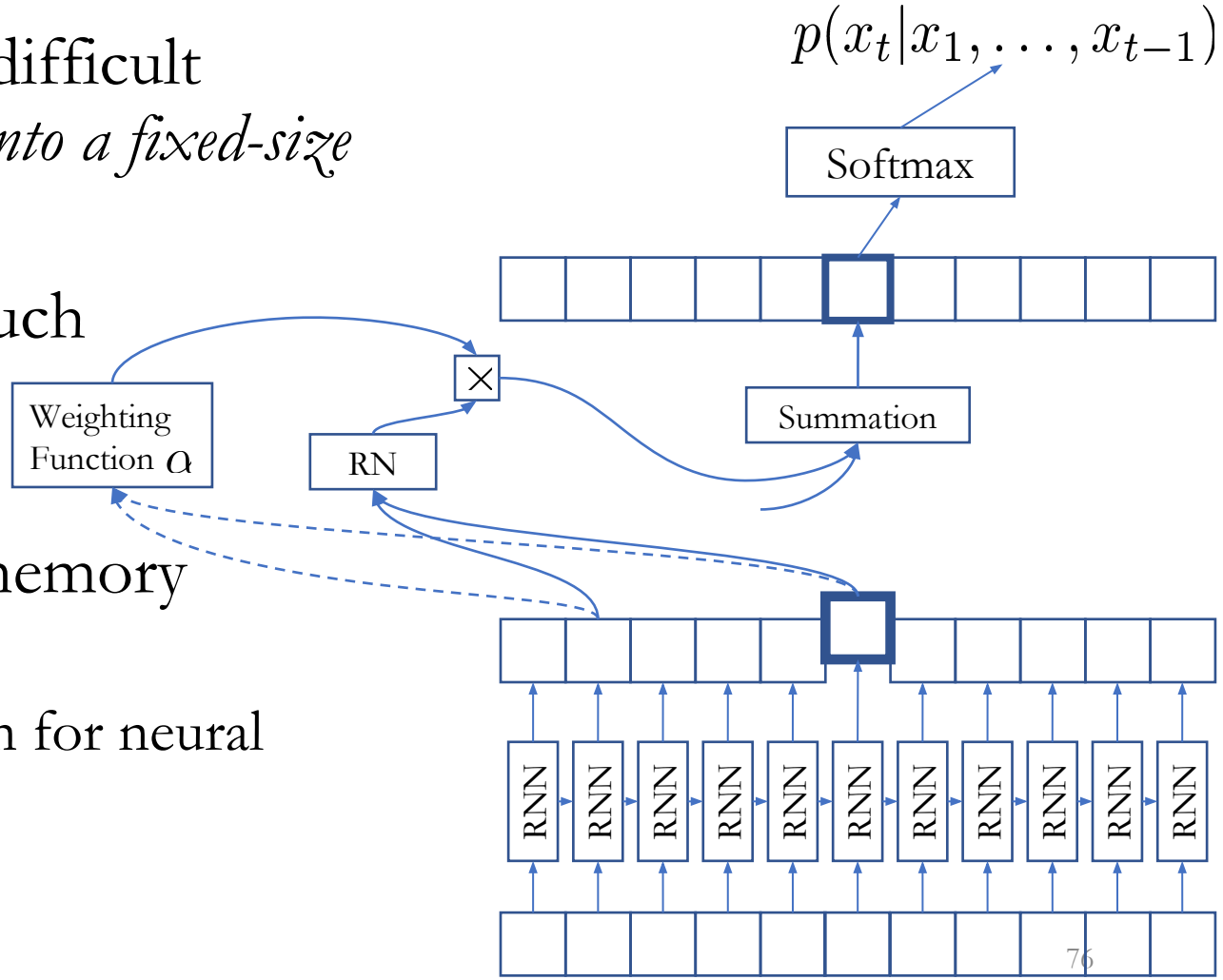
Infinite context n→∞
– Recurrent Language Models [Mikolov et al., 2010]

- A recurrent network summarizes all the tokens so far.
- Use the recurrent network's memory to predict the next token.
- Efficient online processing of a streaming text:
  - Constant time per step.
  - Constant memory throughout forward computation
- Useful in practice:
  - Useful for autocomplete and keyword suggestion.
  - Scoring partial hypotheses in generation.



Infinite context $n \rightarrow \infty$ – Recurrent Memory Networks [Tran et al., 2016]

- The **recurrent network** solves a difficult problem: *compress the entire context into a fixed-size memory vector.*
- **Self-attention** does not require such compression but still can capture long-term dependencies.
- Combine these two: a recurrent memory network (RMN) [Tran et al., 2016]
  - RNMT+: a similar, recent extension for neural machine translation



In this lecture, we learned

- What autoregressive language modelling is:

  $p(X) = p(x_1)p(x_2|x_1)\cdots p(x_T|x_1,\ldots,x_{T-1})$
- How autoregressive language modelling transforms unsupervised learning into a series of supervised learning:
  - It is a series of predicting the next token given previous tokens.
- How neural language modelling improves upon n-gram language models:
  - Continuous vector space facilitates generalization to unseen n-grams.
  - Infinitely large context window
- How sentence representation extraction is used for language modelling:
  - Convolutional language models, recurrent language models and self-attention language models..